Mechanisms of changes of hole concentration in Al-doped 6H-SiC by electron irradiation and annealing

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A B S T R A C T

The temperature dependence of the hole concentration $p(T)$ in Al-doped p-type 6H-SiC irradiated by 100 or 200 keV electrons is investigated. Since $p(T)$ is unchanged by 100 keV electron irradiation, the threshold displacement energy in SiC is higher than 20 eV. Therefore, 200 keV electrons cannot displace substitutional Si and Al in Al-doped 6H-SiC. Using $p(T)$, two types of acceptor species are detected, and the density and energy level of each acceptor species are determined. By 200 keV electron irradiation, the density ($N_{DA}$) of the shallow acceptor (i.e., Al acceptor) decreases monotonously with increasing fluence of electrons, whereas the density ($N_{DA}$) of the deep acceptor initially increases and then decreases. By irradiation with the $1 \times 10^{16} \text{ cm}^{-2}$ fluence of 200 keV electrons, especially, the decrement of $N_{DA}$ is nearly equal to the increment of $N_{DA}$. By annealing at 500 °C, on the other hand, the increment of $N_{DA}$ is close to the decrement of $N_{DA}$.

1. Introduction

Silicon carbide (SiC) is a promising wide bandgap semiconductor for fabricating high-power and high-frequency electronic devices capable of operating at elevated temperatures under radiation environment.

By comparing electron-radiation damage in p-type 4H-SiC with that in p-type Si [1–4], it was found that the reduction in the temperature-dependent hole concentration $p(T)$ in Al-doped p-type 4H-SiC by electron irradiation was much larger than in Al-doped p-type Si.

In the analyses of $p(T)$ in lightly Al-doped p-type 4H-SiC epilayers, the density ($N_{Al}$) of Al acceptors with the energy level ($E_{Al}$) of $E_V + 0.22 \text{ eV}$ significantly decreased with increasing fluence ($\Phi$) of 200 keV electrons, whereas the density ($N_{DA}$) of deep acceptors with the energy level ($E_{DA}$) of $E_V + 0.38 \text{ eV}$ initially increased with $\Phi$ and then decreased [4,5], where $E_V$ is the valence band maximum. The reduction in $p(T)$ by 200 keV electron irradiation was mainly due to the decrease in Al acceptors and not due to the increase in C vacancies ($N_V$) created by irradiation [4,5]. In unirradiated epilayers, on the other hand, the relationship of $N_{DA} = 0.6N_{Al}$ was obtained in a range of $N_{Al}$ between $8 \times 10^{15}$ and $5 \times 10^{16} \text{ cm}^{-2}$ [6,7], suggesting that the deep acceptors may be related to Al. From these experimental results, differential equations describing the dependence of $N_{Al}$ and $N_{DA}$ on $\Phi$ were proposed as [5]

$$\frac{dN_{Al}}{d\Phi} = -\kappa_{Al}N_{Al}$$

(1)

and

$$\frac{dN_{DA}}{d\Phi} = -\frac{dN_{Al}}{d\Phi} - \kappa_{DA}N_{DA}$$

(2)

where $\kappa_{Al}$ and $\kappa_{DA}$ are the removal cross sections of Al acceptors and deep acceptors for 200 keV electron irradiation, respectively. By fitting the curve to the experimental dependence of $N_{Al}$ or $N_{DA}$ on $\Phi$, the values of $\kappa_{Al}$ and $\kappa_{DA}$ were determined to be $4.4 \times 10^{-17}$ and $1.0 \times 10^{-17} \text{ cm}^2$, respectively [5].

From $p(T)$ for lightly Al-doped 6H-SiC epilayers, an acceptor species with $E_V + 0.2 \text{ eV}$ was observed [8,9]. From photoluminescence [10], the acceptor species is ascribed to an Al atom (Al$_{Si}$) at a Si sublattice site. In heavily Al-implanted p-type 6H-SiC layers, the removal cross section of Al acceptors for 1 MeV electron irradiation was determined to be $6.4 \times 10^{-18} \text{ cm}^2$ [11]. Since 6H-SiC is expected to be a suitable polytype for electronic devices used in high-energy radiation environments besides 4H-SiC, we report on the reduction in $p(T)$ in lightly Al-doped p-type 6H-SiC epilayers by 100 or 200 keV electron irradiation.

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2. Experimental

A 4.9 μm-thick lightly Al-doped p-type 6H-SiC epilayer on n-type 6H-SiC (resistivity: 0.027 Ω·cm) was cut to a 1 × 1 cm² size. Ohmic metal (Ti/Al) was deposited on the four corners of the surface of the sample, and then the sample was annealed at 900 °C for 1 min in an Ar atmosphere. The p(T) was measured by van der Pauw configuration in the temperature range from 200 to 600 K in a magnetic field of 1.4 T using a modified MMR Technologies’ Hall system. After the sample was irradiated with 200 keV electrons with a fluence of 1.0 × 10¹⁴ cm⁻² at room temperature, the Hall-effect measurement was carried out. The sample was again irradiated with the same fluence, and then the measurement was done. These processes were repeated. Consequently, p(T) values for total fluences (θ) of 0, 1.0, 2.0, and 3.0 × 10¹⁶ cm⁻² were measured. However, p(T) at θ of 3.0 × 10¹⁶ cm⁻² could not be obtained. After annealing the sample at 500 °C for 2 min in an Ar atmosphere, therefore, the Hall-effect measurement was carried out. Another sample was irradiated with 100 keV electrons with θ of 0, 1.0, 3.0, and 5.0 × 10¹⁶ cm⁻², and these p(T) values were obtained.

The densities and energy levels of acceptors and hole traps were determined by free carrier concentration spectroscopy (FCCS) from p(T). Here, FCCS is a graphical peak analysis method to determine them without any assumptions regarding acceptor species or hole traps. Using p(T), the FCCS signal is defined as

\[ H(T, E_{\text{rel}}) = \frac{p(T)^2}{(kT)^2} \exp \left( \frac{E_{\text{rel}}}{kT} \right), \]

where \( k \) is the Boltzmann constant and \( E_{\text{rel}} \) is the parameter that can shift the peak temperature of the FCCS signal within the temperature range of the measurement. The FCCS signal has a peak at the temperature corresponding to each acceptor level or hole-trap level. From each peak, the density and energy level of the corresponding acceptor or hole trap can be accurately determined. The application software of FCCS for the Windows operating system can be downloaded for free at our Web site (http://www.osakac.ac.jp/labs/matsuura/).

3. Results and discussion

Fig. 1 shows the experimental p(T) before irradiation (○) and after irradiation with 200 keV electrons with θ of 1.0 × 10¹⁶ cm⁻² (▲) and 2.0 × 10¹⁶ cm⁻² (□). Since p(T) at θ of 3.0 × 10¹⁶ cm⁻² could not be measured, the sample was annealed at 500 °C for 2 min. The p(T) in the annealed sample is denoted by + in Fig. 1. Although the Hall-effect measurements were carried out twice for each fluence, p(T) remained unchanged, indicating that any acceptors and defects affecting p(T) were not annealed for measurement temperatures lower than 600 K, that is, 327 °C.

Using the p(T) for the unirradiated sample in Fig. 1, the acceptor densities and energy levels were determined by FCCS. The obtained values of \( N_{DA}, E_{DA}, N_{DA}, \) and \( E_{DA} \) were 1.6 × 10¹⁵ cm⁻³, \( E_{V} + 0.24 \) eV, 1.0 × 10¹⁵ cm⁻³, and \( E_{V} + 0.41 \) eV, respectively. Moreover, the compensating density \( (N_{\text{comp}}) \), which is the sum of the densities of donors and hole traps deeper than \( E_{DA} \), was 2.6 × 10¹⁵ cm⁻³.

p(T) was numerically simulated using the following two equations:

\[ p(T) + N_{\text{comp}} = N_{DA} f_{FD}(E_{DA}) + N_{DA} f_{FD}(E_{DA}) \]

and

\[ p(T) = N_{DA} f_{FD}(E_{DA}) \exp \left[ \frac{E_{DA} - E_{V}}{kT} \right] . \]
Moreover, other C atoms activated by the irradiation migrate and react with \( \mathrm{Al}_{\mathrm{Si}}-\mathrm{C}_i \), suggesting that \( N_{D_{\mathrm{DA}}} \) decreases. This model also leads to Eqs. (1) and (2).

Although \( N_{A_1} \) and \( N_{D_{\mathrm{DA}}} \) in the sample irradiated with \( \Phi \) of \( 3 \times 10^{16} \, \text{cm}^{-2} \) could not be determined, they are expected to be \( 4.3 \times 10^{13} \) and \( 2.1 \times 10^{15} \, \text{cm}^{-2} \), respectively, by simulation using Eqs. (1) and (2) with \( \kappa_{\mathrm{AI}} \) of \( 1 \times 10^{-15} \, \text{cm}^2 \) and \( \kappa_{\mathrm{DA}} \) of \( 9 \times 10^{-18} \, \text{cm}^2 \). The simulations of the dependence of \( N_{A_1} \) and \( N_{D_{\mathrm{DA}}} \) on \( \Phi \) are shown by solid and broken lines, respectively. After annealing the sample at 500 °C for 2 min, \( N_{A_1} \) and \( N_{D_{\mathrm{DA}}} \) could be determined to be \( 4.0 \times 10^{14} \) and \( 1.5 \times 10^{15} \, \text{cm}^{-3} \), respectively. By annealing at 500 °C, \( N_{A_1} \) is considered to be increased, and \( N_{D_{\mathrm{DA}}} \) is decreased. From Fig. 2, furthermore, the increment of \( N_{A_1} \) is expected to be nearly equal to the decrement of \( N_{D_{\mathrm{DA}}} \). This suggests that the 500 °C annealing transforms the deep acceptors into the Al acceptors.

According to literature [15–17], almost all defects were annealed out at higher than 750 °C. Only a few defects were unchanged by irradiation with \( 100 \) or \( 200 \, \text{keV electrons} \), 100 cm and 100 cm, respectively. Compared to \( \mathrm{V}_C \), \( \mathrm{C}_i \) is rather mobile but can migrate and react with other defects or impurities [18]. By annealing at 500 °C, the following processes possibly occur in order to recover \( N_{A_1} \) and to reduce \( N_{D_{\mathrm{DA}}} \): \( \mathrm{C}_i \) migrates and reacts with \( \mathrm{Al}_{\mathrm{Si}}-\mathrm{V}_C \) or \( \mathrm{Al}_{\mathrm{Si}}-\mathrm{C}_i \) releases \( \mathrm{C}_i \). Further research is in progress.

4. Conclusion

The changes of \( p(T) \) in Al-doped p-type 6H-SiC by irradiation with 100 or 200 keV electrons were investigated. Since \( p(T) \) was unchanged by irradiation with 100 keV electrons, 100 keV electrons could not displace any substitutional atoms in 6H-SiC. This indicated that \( E_a \) in SiC was higher than 20 eV, which meant that 200 keV electrons could not displace \( \mathrm{Al}_{\mathrm{Si}} \) and \( \mathrm{Si}_\mathrm{A} \) in Al-doped SiC. Therefore, 200 keV electrons could displace only \( \mathrm{C}_i \). By \( \mathrm{C}_i \) displacement in Al-doped 6H-SiC, \( N_{D_{\mathrm{DA}}} \) decreased monotonously with \( \Phi \), while \( N_{A_1} \) initially increased and then decreased. By irradiation with 200 keV electrons with \( \Phi \) of \( 1 \times 10^{16} \, \text{cm}^{-2} \), especially, the decrement of \( N_{A_1} \) was nearly equal to the increment of \( N_{D_{\mathrm{DA}}} \). By annealing at 500 °C at 2 min, moreover, the increment of \( N_{A_1} \) was close to the decrement of \( N_{D_{\mathrm{DA}}} \).

References


